Hairpin Vortex Identification using Template Fitting on Vortex Corelines

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ABSTRACT

We apply an improved vortex coreline extraction method with an additional template fitting to identify hairpin vortices that are hard to extract robustly. We demonstrate the effectiveness of our method by showcasing the results on a stress-driven turbulent Couette flow.

Keywords: Turbulent flow, vortex identification, Hairpin vortex

1 INTRODUCTION

Hairpin vortices (Fig. 1(a)) are important vortical structures that are formed due to turbulence near the boundary layer in fluid flows [3]. Identifying and visualizing hairpin vortices provides useful insight about the transition process of fluid flows from laminar to turbulent around the fluid boundary layers [1]. However, in practice, boundary layers in turbulence flows have complex configurations, resulting in hairpin vortices in irregular shapes and even tangled with other vortices, making their extraction difficult. Currently, there is not a robust and automatic framework to extract and separate hairpin vortices. Existing methods that rely on thresholding strategy applied to certain physical attributes usually lead to incomplete (or disconnected) vortices due to the sensitivity of the selection of a proper threshold value (Fig. 1(c)). To address this challenge, we propose a framework that performs vortex coreline extraction followed by a template fitting step to identify candidate hairpin vortices.

Existing coreline extraction methods usually apply Parallel Vectors Operator to identify candidate corelines then perform a filtering to remove false positive corelines. However, depending on the selected filtering strategy, the resulted corelines may be either disconnected (due to strict criteria) or still contain outliers (due to weak criteria). To address that, we study different filtering criteria, such as Q, Δ, λ_2 criteria [2], and their combination to identify a filtering strategy that allows to retain long and connected corelines while removing outliers (or noise). After obtaining the corelines, we fit a standard template of hairpin vortex on each extracted coreline to identify those that match (i.e., having a high similarity to) the template. Before template fitting, we use a pre-processing step to eliminate corelines that are almost straight.

Our method represents an attempt to utilize the geometry characteristics of hairpin vortices to identify them, which will be combined with the physical characteristics of hairpin vortices to develop a complete and comprehensive framework for their extraction and study in the future. To demonstrate the effectiveness of our method, we show qualitative results on the velocity profile from the numerical simulation of a stress-driven turbulent Couette flow [3].

2 BACKGROUND AND METHOD

Vortex extraction is one of the most challenging tasks of fluid flow analysis. Some methods of vortex extraction focus on vortex coreline extraction while others focus on region-based approaches [2]. Due to the difficulty of selecting a proper threshold value to identify vortices, in this work we resort to the coreline extraction to identify vortices. As mentioned in [2], one of the most robust methods of vortex coreline extraction is based on the "Parallel Vectors" (PV) operator. Let $\boldsymbol{v}$ be the velocity and $\boldsymbol{J}$ Jacobian of the flow, then the acceleration $\boldsymbol{a}$ of the flow is given by $\boldsymbol{a} = \boldsymbol{J}\boldsymbol{v}$. The vortex coreline is the set of points, called PV points, where the two vector fields are parallel, that is,

$$S = \{\boldsymbol{x} : \exists\lambda, \boldsymbol{v}(\boldsymbol{x}) = \lambda \boldsymbol{a}(\boldsymbol{x})\} \tag{1}$$

In 3D, the set of PV points form polylines which belong to vortex cores. Using just the PV operator for vortex coreline extraction may introduce false positives, which requires further filtration using Q, Δ, and λ_2 criteria [2]. The set of points belong to the vortical-region where $Q > 0$, $\Delta > 0$ or $\lambda_2 < 0$. In VTK, the filtration process uses these criteria in the following order $Q \rightarrow \Delta \rightarrow \lambda_2$. Generally, $Q > 0$ is more restricting as compared to $\Delta > 0$ and $\lambda_2 < 0$ as mentioned in [2]. Using Q-criterion fails to produce contiguous corelines, while removing Q-criterion results in contiguous lines but introduces noise and false positives.

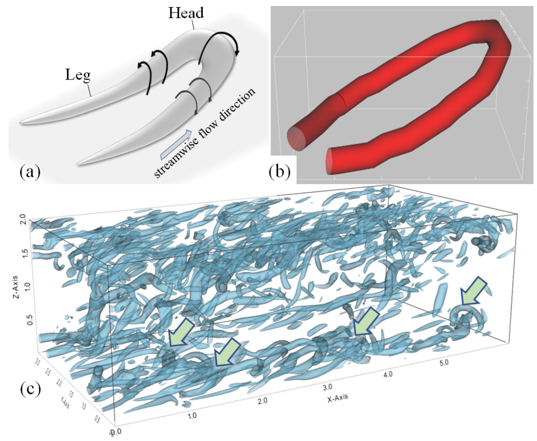

Figure 1: (a) Illustration of a hairpin vortex, (b) isosurface of a hairpin vortex using λ_2, and (c) isosurfaces of λ_2 of a stress-driven turbulent Couette flow [3]. Arrows point to places that hairpin vortices may arise.

Vortex Corelines Extraction: In order to get the contiguous corelines while at the same time removing the noise, we merge the outputs of two sets of corelines. One set is the result with the default VTK implementation, which uses parallel vectors operator and post filtration based on $Q \rightarrow \Delta \rightarrow \lambda_2$ criteria, while the second set is the result of a custom filtration order that uses only $\Delta \rightarrow \lambda_2$ criteria, which is less restricting. Finally, we merge the two sets of polylines by intersecting them but retain the lines only from the second set. This results in the removal of noise (depending on the first set) and retention of the contiguous lines (from the second set).

After obtaining the candidate corelines using the above improved method, we next will extract the corelines that may correspond to hairpin vortices. This process consists of two steps: *pre-filtration* and *template fitting*.

Pre-filtration: Hairpin vortices resemble the shape of a hairpin (see Fig. 1(a)), thus the name "hairpin". Many false vortices can be filtered based on the winding angle of the coreline. Let (p_{i-1}, p_i) are two points in the coreline that form a line, then the winding angle of the coreline can be calculated as $\sum_{i=0}^{n-1} \angle(p_{i-1}, p_i, p_{i+1})$, where n is the number of points in the coreline. The vortex corelines that resemble straight line have small winding angle value, thus they can

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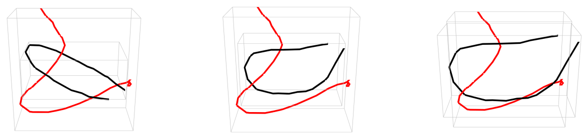


(a) (b) (c)

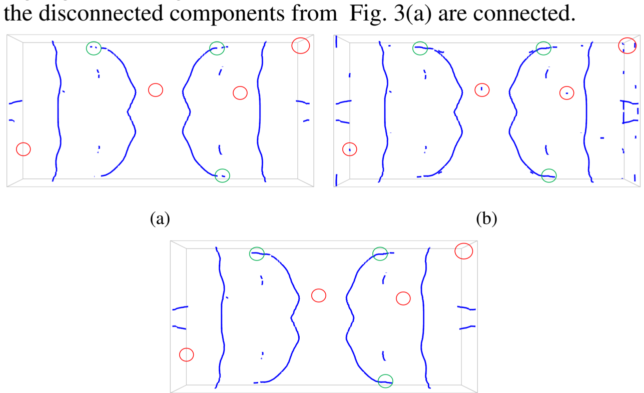
Figure 2: (a) shows the template (black) and target (red) corelines in their original scale and orientation. (b) and (c) show the aligned orientation and scaling after transformation, respectively. The template has the minimum distance with the target in this orientation and size.

be filtered using a threshold value. Pre-filtration using the winding angle reduces the number of candidates for template fitting which is comparatively computationally expensive.

Template Fitting: In order to identify hairpin vortices, we use a standard template shown in Fig. 2 and fit to each coreline obtained from the above filtration. This results in a distance matrix between two polydatas (i.e., the template and the target corelines), which can be used to discard those corelines which do not match the template. The template fitting process works as follows. First, bounding boxes are drawn around the template and target corelines. Next, we rotate the template's bounding box in 10 different orientations (4 around X-axis, 3 around Y-axis and 3 around Z-axis). In each orientation we use landmark transformation, to transform the template in such a way that each corner of its bounding box gets aligned with the target's bounding box. Landmark transform performs the rotation, translation and isotropic scaling to match the source and target landmarks. Hausdorff distance is calculated in each orientation and the minimum value is considered for each target coreline. Fig. 2 shows the template fitting process with the target coreline.

3 Results and Discussion

Fig. 3 shows qualitative results for our vortex corelines extraction method for the simpler Bernard dataset. Fig. 3(a) shows the corelines extracted using more restricting criteria of $Q \rightarrow \Delta \rightarrow \lambda_2$ from VTK as mentioned in section 2. The disconnected corelines are highlighted by green circles. Fig. 3(b) shows the corelines extracted using less restricting criteria of $\Delta \rightarrow \lambda_2$. Some of the false positives are highlighted in by red circles. Fig. 3(c) shows the corelines after our merging strategy. It can be clearly seen that the false positives highlighted in Fig. 3(b) have been removed and at the same time the disconnected components from Fig. 3(a) are connected.



(a) (b) (c)

Figure 3: Vortex corelines for Bernard dataset. (a) shows the vortex corelines extracted using stricter criteria of VTK. (b) shows the vortex corelines using less stricter criteria without Q. (c) shows the merger of two sets of corelines.

We apply our method to the vector field dataset of the numerical simulation of stress-driven turbulent Couette flow by Yang et. al. [3]. The dataset is the result of turbulent flows over progressive surface wave. Fig. 4 shows the results of vortex corelines extraction (Fig. 4a) and the output of the hairpin identification (Fig. 4b). It can be seen from Fig. 4(a) that the turbulence generates many different types of vortical structures in the flow. We apply the pre-processing and the template fitting to identify hairpin vortices from the flow. As shown in Fig. 4b, our method identifies some candidate corelines that may correspond to hairpin vortices (see Zoom-in view of some corelines). In the meantime, it still contains quite many false positive, which we plan to look into in the future.

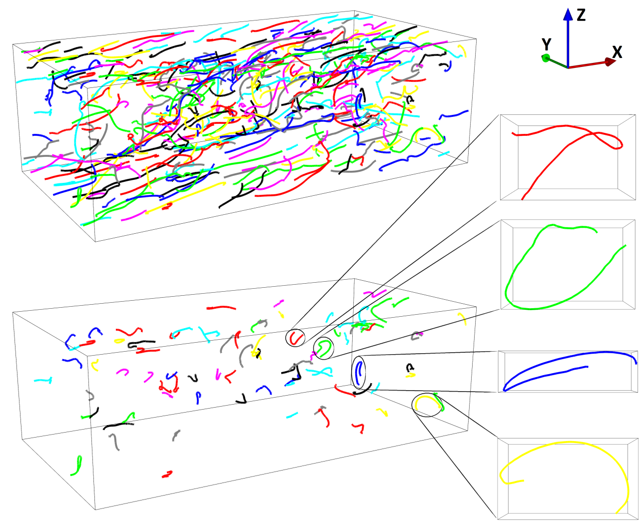


Figure 4: (a) shows the result of the vortex corelines extraction. (b) shows the result of the extracted hairpin vortices. We use different colors for each coreline to differentiate different vortex corelines.

4 Conclusion and Future Work

In this work, we propose the identification of hairpin vortices using template fitting on vortex corelines. In order to get the contiguous corelines, we merge two sets of output corelines which are extracted using strict and conservative criteria. Afterwards, the first filtration layer removes the candidate corelines based on the winding angle method and the second filtration layer removes the corelines based on the template fitting method. We demonstrate the results by applying our method on the vector field of a wall-bounded turbulent flow.

Given the complexity of coherent vortical structures in turbulent flows, hairpin vortices can take up many different shapes and sizes. One template might not fit all types of hairpin vortex shapes. Moreover, the local methods of vortex corelines extraction used in this work are prune to error and noise. In the future, we plan to adapt the recently introduced exact analytic parallel vectors along with additional geometric criteria (e.g., checking rotation centers) to improve the robustness of coreline extraction. With robust vortex corelines extraction framework, we will be able to use them as the geometric characteristics to combine with the physical characteristics of hairpin vortices for their robust extraction and separation.

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